

CONSTRAINTS ON THE EXTRAGALACTIC INFRARED BACKGROUND FROM GAMMA-RAY OBSERVATIONS OF MKN 501

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ABSTRACT

We use the new results of the HEGRA detector on the TeV γ -ray emission from MKN 501 to set upper limits on the energy density of the cosmic infrared background (CIRB). Contrary to previous interpretations of the γ -ray spectrum of MKN 421 as showing an intergalactic absorption cutoff at 5 TeV, the observed spectrum of MKN 501 extends beyond 10 TeV and appears to be unattenuated by $\gamma\gamma$ collisions with the low-energy CIRB photons. The upper limits on the CIRB intensity – derived both assuming an *a priori* shape for the CIRB spectrum and without model-dependent assumptions – are thus quite strong and come almost in conflict with the observational evaluations based on deep surveys of extragalactic sources in the near- and mid-IR. If spectra at TeV energies for extragalactic *gamma*-ray sources like this for MKN 501 will be confirmed with improved statistics, we may be forced to conclude that the process of $\gamma\gamma$ interaction in the intergalactic space is more complex than expected and the average intergalactic magnetic field extremely weak ($B < 10^{-11}$ G).

Subject headings: infrared: general — gamma rays: observations — scattering

1. Introduction

Cosmic history from the decoupling ($z = 1500$) to the epoch of lighting of the first luminous sources (at redshifts $z \sim 3$ to 5) is one of the biggest unknowns of present-day observational cosmology. High redshifts and dust extinction during early active phases both degrade the energetic optical–UV photons emitted by massive stars, decaying particles, or more exotic energy sources, to the infrared wavelengths. A fundamental information on the total energy budget associated with astrophysical processes occurring at high redshifts is then provided by observations of the cosmic background at infrared wavelengths (CIRB).

Unfortunately, the infrared domain presents various levels of difficulty to the observational astronomer, because of the huge backgrounds from the Earth's atmosphere, the Interplanetary dust (IPD), and diffuse dust in the Milky Way, in addition to the background produced by

the telescope itself. Also the sensitivity and stability of infrared detectors are far poorer than those used in the optical. Because of all this, the detection and characterization of the diffuse background flux of low-energy photons coming from primeval structures has been exceedingly difficult so far. Even dedicated experiments exploiting cooled platforms outside the atmosphere, among which the most important is DIRBE on COBE (Hauser 1996), have failed so far to detect significant signals from the CIRB above the intense foregrounds. The upper limits allowed by the foreground emission deconvolution of DIRBE maps are significantly higher than expectations over a substantial – and crucial – λ –range from a few to $\simeq 100 \mu\text{m}$. The situation, at these wavelengths in particular, is not likely to improve in the future, until a mission flying to the outer Solar System will get rid of the fundamental limitation set by the IPD (both the scattered light and dust re-radiation).

Under these circumstances, a very interesting alternative to the direct detection of CIRB photons has been suggested by Stecker and de Jager (1993) soon after the discovery of high-energy photon fluxes coming from distant Blazars (with GRO, Hartman et al. 1992 and with the Whipple Observatory, Punch et al. 1992). The idea is to infer the CIRB spectral intensity from combined GeV and TeV observations of a set of active galactic nuclei (AGN), by exploiting the $\gamma - \gamma$ interactions and pair production between the AGN high-energy photons and low-energy background photons in the line-of-sight to the source. The interaction is expected to produce an absorption feature, testable in principle, in the source TeV spectrum. Interesting limits have been discussed by Stecker and de Jager (1993), de Jager, Stecker and Salamon (1994), and Dwek and Slavin (1994), *all based on TeV observations of the Blazar MKN 421*.

To summarize, the best current upper limits on the CIRB in the spectral range from 10 to 40 micron are those reported by de Jager, Stecker & Salamon (1994), with a 2σ upper limit of $\lambda I_\lambda < 2 \cdot 10^{-8} \text{ W/m}^2/\text{sr}$. In the same large waveband interval, marginal detections, at levels of $2 \cdot 10^{-9} < \lambda I_\lambda < 2 \cdot 10^{-8} \text{ W/m}^2/\text{sr}$ were reported by de Jager, Stecker & Salamon (1994) and Dwek & Slavin (1994). At shorter wavelengths, 1 to $10 \mu\text{m}$, upper limits have been obtained by Stecker & de Jager (1993), Stecker (1996), Dwek & Slavin (1994) and Biller et al. (1995). The most conservative bounds, accounting for the precise spectral shape of the CIRB, given by Dwek & Slavin (1994, $\lambda I_\lambda < 10^{-7} \text{ W/m}^2/\text{sr}$), still keep a substantial factor (>10) higher than the expected contribution of known sources.

While all previous analyses relied uniquely on TeV observations of the blazar MKN 421, we exploit here a new high-quality dataset of TeV gamma-ray observations by HEGRA of MKN 501 during a state of high activity (Aharonian et al 1997a) to further constrain the intensity of the diffuse IR background.

Two sets of constraints on the CIRB spectral intensity are derived in Section 2. One is based on the assumption that the background spectrum is dominated by the contribution of distant galaxies, and thus reflects the average galactic IR spectrum. The other constraint is free of model-dependent assumptions and treats the CIRB as a combination of twelve bins wherein

the background spectrum is flat (in λI_λ) with independent arbitrary normalizations. Extremely tight constraints on the CIRB ensue from this analysis, reflecting the missing evidence of any absorption in the TeV spectrum of MKN 501. A discussion is given in Section 3 in terms of a low average past emissivity both of galaxies and of primeval energy sources. Indeed the limits are so severe that they begin to conflict with the integrated IR flux of distant galaxies, recently detected in large numbers by ground-based and space observatories. We finally emphasize the alternative possibility that the interaction of high-energy gamma-rays with low-energy photons is more complex than previously supposed. $H_0 = 75 \text{ km/s/Mpc}$ is assumed throughout the paper.

2. Data analysis and results

We use the data set taken in March and April 1997 with the HEGRA stereoscopic system of four imaging Cherenkov telescopes (Hermann 1995). At that time MKN 501 was in an extremely high state, the far brightest gamma-ray source in the sky. The flare was observed by all TeV γ -ray observatories in the Northern hemisphere (Breslin et al. 1997). The high gamma-ray flux allowed the HEGRA observatory to measure the gamma-ray energy spectrum in short time intervals. The spectrum measured between March 15 to 20 covers 1.2 orders of magnitude in photon energy, from 0.8 to 12.6 TeV, divided into twelve logarithmically spaced energy bins. The photon number spectrum at TeV γ -ray energies is consistent with a power law of differential spectral index $\alpha = 2.49 \pm 0.11$. This spectrum is shown in Figure 1 (data points) together with the allowed range of best-fitting power-laws derived by the observational team (shaded region). Similar power-law spectra for MKN 501 have been observed by various other groups (see e.g. Protheroe et al. 1997).

The main difficulty with the derivation of the CIRB spectral intensity from TeV γ -ray absorption is the lack of knowledge of the production spectrum, which may deviate from a pure power-law and/or show absorption at the source. Spectra measured within short time intervals, during which the source’s activity state is not likely to vary, are very valuable in this respect, although there is not an evidence for strong spectral variability of the MKN501 emission (Aharonian et al. 1997b). For this reason we confined our analysis to a spectrum based on data collected between March 15 to 20, rather than the one using the whole March-April database in the updated version of Aharonian et al (1997a).

As a first step in understanding the observed spectrum, we attempted to derive the allowed range of differential spectral indices α at the source and the CIRB absorption by fitting the observed γ -ray spectrum with a variety of assumptions for α and for the intensity I_{IR} of the extragalactic IR background. We first assumed that the source spectrum in the observed range is a pure power-law and that the low-energy background is dominated by the integrated contribution of distant galaxies. In such a case, the shape of the CIRB is well constrained, and should reflect the average galactic spectrum, which has a minimum at $\lambda \sim 10 \mu m$ corresponding to the intersection of the stellar with the dust emission component. We refer here to the detailed spectral shape estimated by Franceschini et al (1991).

Then the fit was performed in a two parameter space consisting of the source gamma-ray spectral index α and the CIRB intensity I_{IR} normalized to the model spectrum $I_0(\lambda)$ by Franceschini et al (1991). For a given spectral index α the absorption due to the CIRB was first calculated and the resulting spectrum was then normalized to the detected γ -ray flux above 1 TeV. This procedure enabled us to avoid introducing a third parameter, the source spectrum normalization. Table 1 shows the optical depth assuming $I_{IR}/I_0 = 1$, for all twelve experimental energy bins.

Figure 2 summarizes the results of fitting the observed MKN 501 spectrum. It plots contours of the χ^2 2D distribution in the parameter plane, including the unphysical region corresponding to negative I_{IR}/I_0 values, where gamma-rays are ‘created’ in collisions with CIRB photons. The darker an area is the better the fit is (except for fits with $\chi^2 < 1.45$, corresponding to the blank inner region). The formal best fit ($\chi^2_\nu = 1.41$ p.d.f. for 10 degrees of freedom, confidence level 0.16) is in the “unphysical” region: $\alpha = 2.52$, $I_{IR}/I_0 = -0.3$. The best fit in the “physical” region occurs at $I_{IR}/I_0 = 0$ (no-absorption, $\chi^2_\nu = 1.42$ p.d.f.) and yields $\alpha = 2.48$, in agreement with the result of the experimental group. Flatter TeV γ -ray source spectra allow for higher intergalactic absorption: a value for the spectral index of $\alpha = 2.16$, corresponding to $I_{IR}/I_0 = 1.70$, is the hardest spectrum with $\chi^2_\nu < 1.80$ (corresponding to the 95% confidence limit). The best-fit spectra corresponding to $I_{IR}/I_0=0$ and the flattest one assuming $I_{IR}/I_0 = 1.7$ are also shown in Fig. 1.

It is important to understand that the fit quality, and correspondingly the limits on the CIRB, depend crucially on the manner in which the ‘theoretical’ power-law fluxes are normalized in the fitting procedure. The normalization to the observed γ -ray flux above 1 TeV causes very different spectral indices to fit the observations equally well and generates a broad χ^2 valley in Fig.2. This would change significantly if the observed γ -ray energy range were extended on either side. An observation at $E_\gamma \geq 300$ GeV (the threshold energy of the Whipple telescope) would improve the overall normalization and allow us to distinguish better between different spectral indices ‘at production’. An extension to higher γ -ray energy, hence larger optical depths (see Table 1) would make easier the detection of any absorption by the CIRB.

We finally attempted to obtain model-independent limits on the CIRB, with no a-priori guess at the background spectrum. To compute them we conservatively assumed that the high-energy source spectrum is the flattest allowed by the fits of Fig. 1, i.e. $\alpha = 2.16$. We normalize the spectrum at the source to be $F_\gamma + 1.64 \times \delta F_\gamma$ in the first experimental bin. This normalization factor is a source of uncertainty. It is partially justified by the fact that MKN 501 is close enough (136 Mpc) compared to the optical depth (600 Mpc for $\lambda I_\lambda = 7.64 \cdot 10^{-9} \text{ W m}^{-2} \text{ sr}^{-1}$) that the content of this bin would be absorbed only by 20%.

The absorption of γ -rays of energy E TeV is due to IR photons within a certain wavelength interval around the maximum absorption at $\epsilon_{max} = 2(m_e c^2)^2/E_\gamma$ ($\lambda_{max} = 1.24/(\epsilon_{max}, \text{eV}) \mu\text{m}$). We have then assumed that the absorption of any given γ -ray energy bin is caused by CIRB with flat $\lambda I(\lambda)$ spectrum. The envelope of all upper limits to the CIRB intensity obtained in this

way is shown as a histogram in Fig. 3. The limits are assigned within wavelength intervals that contribute 90% of the optical depth for that bin. As we see, the limits become less stringent at longer wavelengths. The limit in the $3.4\ \mu\text{m}$ to $24\ \mu\text{m}$ range comes from one single energy bin (5.0 to 6.3 TeV) where a particularly large γ -ray flux was measured.

Note that the obtained upper limits fall already very close to recent direct evaluations of the IR background based on deep IR surveys (Franceschini et al. 1997). As shown in Fig. 3, the upper limits heavily rely on the error in the TeV flux measurement and are less stringent for $\lambda > 10\ \mu\text{m}$, where the TeV γ -ray statistics is not as good.

3. Discussion

In either case, both assuming the CIRB shape and relaxing it, the constraints on the CIRB intensity appear dramatic. Essentially the MKN 501 gamma-ray spectrum does not display the expected effect of absorption, it rather shows a simple $E^{-2.5}$ power-law spectrum.

How reliable are these limits in view of the possible systematic errors of $\sim 25\%$ in the energy estimates of the HEGRA telescopes (Aharonian et al. 1997c)? This is very easy to estimate in the case of a flat binned λI_λ CIRB spectrum. The limits in Figure 3 would move upward and towards shorter wavelengths with the fractional amount of energy overestimate. Similar relaxation would occur also in the case of a more specialized model CIRB spectrum. One could use the optical depths from Table 1 to estimate the amount of relaxation. Similarly, a higher normalization of the source spectrum would relax the model-independent limits by the ratio of the two normalizations.

Is this featureless spectrum of MKN 501 inconsistent with that observed for MKN 421, which is almost at the same distance? The latter has been interpreted by some authors (e.g. Stecker 1996) as showing a turnover at $\epsilon \simeq 3 - 5\ \text{TeV}$, which was attributed to $\gamma\gamma$ absorption with the CIRB. In fact, new observations of this source during a high activity state do not appear to confirm the presence of absorption (Krennrich et al. 1997), and show significant counting rate above 5 TeV. So, at least during this high state, MKN 421 seems to show a power law spectrum similar to the spectrum discussed here for MKN 501.

The constraints on the CIRB intensity from TeV observations of MKN 501 start to approach the "measured" lower limits at 2.2, 6.7 and $15\ \mu\text{m}$ given by the integrated emission of galaxies already resolved in deep integrations at those wavelengths. Deep surveys have been performed from ground in the K-band and from space by the mid-IR camera (ISOCAM, see Cesarsky et al. 1996) on the ISO satellite in the two latter bands. A summary of these "direct" determinations of the galaxy contribution to the CIRB, and a discussion of the related uncertainties, are given by Franceschini et al (1997) and Oliver et al. (1997). In any case, the CIRB cannot be lower than reported at these three wavelengths.

Few possibilities are left. The first one is that the CIRB is very close to the limits allowed by

the gamma-ray spectrum of MKN 501 observed by Aharonian et al. (1997a). This would imply a very strong constraint on any signals unrelated to the emission of distant galaxies (see e.g. Rowan–Robinson & Carr, 1988, for a review).

But, in view of the fact that the same power-law spectral shape as show in Fig. 1 for MKN 501 has been confirmed by later integrations on this source (Aharonian et al. 1997a; Protheroe et al. 1997), that apparently a similar shape is also suggested for MKN 421, and because an appreciable CIRB flux has already been detected and resolved into discrete sources, we find more likely that *we have to revise our concepts about the propagation of TeV gamma-rays into the intergalactic space, and that something complicates the process.*

The question is: why the propagation of TeV gamma-rays in intergalactic space should not produce the expected absorption in high energy spectra of distant sources? A possible solution could be that part of the source spectrum is regenerated in γ -ray cascading (pair production + Inverse Compton). In such a cascading process, the γ -ray spectrum of the source is depleted around the region of maximum absorption. If the γ -ray emission of MKN 501 at the source extends above 10^{14} eV, the spectrum would be depleted in collisions with microwave background photons. The e^+e^- pairs generated on the microwave background would Inverse Compton scatter on the microwave background to regenerate photons of lower (TeV) energy, thus generating ‘bumps’ on a power-law production spectrum (Protheroe & Stanev 1993). The resulting γ -ray spectrum may then appear unattenuated at observation. This would however require not only a γ -ray spectrum extending to very high energy, but also a very low ($\sim 10^{-11}$ Gauss) value for the extragalactic magnetic field in the direction of MKN501. Otherwise the e^+e^- pairs would deflect in the magnetic field and form a halo around the source, well outside of the angular resolution of the HEGRA detector.

A good deal of constraints useful to disentangle between these two possibilities are soon expected by improved observations of the MKN501 outburst (which has been observed by the Whipple and CAT Cherenkov telescopes, Breslin et al. 1997) with different energy thresholds and wavelength bands and by refined forthcoming data on MKN 421.

Acknowledgements. The authors appreciate the contribution of an anonymous referee to the improvement of the paper. TS thanks J. Buckley and T.K. Gaisser for the careful reading of the manuscript and E. Dwek for comments. The research of TS is funded in part by NASA grant NAG5-5106.

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FIGURE CAPTION

Fig. 1.— The energy spectrum of the TeV γ -rays from MKN 501 observed by the HEGRA detector, together with its power-law spectral fits (lightly shaded area). The solid line shows our best fit in the physical region (see text). The dashed line shows the fit with $\alpha = 2.16$ and $I_{IR}/I_0 = 1.70$.

Fig. 2.— The range of spectral indices and CIRB energy densities that allow for 90% confidence fits of the observed TeV γ -ray spectrum of MKN 501, assuming a theoretical shape for CIRB – see text. The best formal fit, shown with a cross, is in the unphysical region. The χ^2 scale is given in the upper right corner.

Fig. 3.— Upper limits for the CIRB density derived from the TeV γ -ray spectrum of MKN 501: a) assuming the theoretical shape shown with a thin line; b) assuming flat λI_λ . The thick line shows the estimate of Franceschini et al (1991) and the three data points are from Franceschini et al (1997). These are three direct evaluations of the CIRB spectral intensity due to faint galaxies at $\lambda = 2.2, 6.7$ and $15 \mu m$, based on galaxy models fitting deep counts performed at these wavelengths.

Table 1: Optical depths and CIRB wavelength ranges responsible for the absorption of TeV gamma rays by MKN 501 for a distance of 136 Mpc ($H_0 = 75$ km/s/Mpc). Column 1 shows the γ -ray energy range, columns 2, 3 & 4 give the optical depth, CIRB wavelength of maximum absorption and the wavelength range responsible for 90% of the optical depth for the model of Franceschini et al (1991). Columns 5, 6 & 7 give the same quantities for constant $\lambda I_\lambda = 7.64 \cdot 10^{-9} \text{ W m}^{-2} \text{ sr}^{-1}$.

E_γ (TeV)	$\tau_{\gamma\gamma}$	model λI_λ		$\tau_{\gamma\gamma}$	$\lambda I_\lambda = \text{const}$	
		λ_{max} (μm)	$\lambda_{90\%}$ (μm)		λ_{max} (μm)	$\lambda_{90\%}$ (μm)
0.79 – 1.00	0.25	1.7	0.53 – 3.8	0.23	2.1	0.53 – 3.8
1.00 – 1.26	0.29	2.0	0.60 – 4.8	0.28	2.7	0.67 – 4.8
1.26 – 1.59	0.32	2.1	0.67 – 6.0	0.36	3.4	0.84 – 6.0
1.58 – 1.99	0.33	2.2	0.75 – 7.5	0.45	4.2	1.1 – 7.5
2.00 – 2.51	0.34	2.4	0.84 – 9.5	0.57	5.3	1.3 – 9.5
2.51 – 3.16	0.35	2.5	0.95 – 12.	0.71	6.7	1.7 – 12.
3.16 – 3.98	0.37	3.0	1.1 – 15.	0.86	8.4	2.1 – 15.
3.98 – 5.01	0.41	13.4	1.2 – 19.	1.13	10.9	2.7 – 19.
5.01 – 6.31	0.48	15.0	1.5 – 24.	1.43	13.4	3.4 – 24.
6.31 – 7.94	0.59	16.8	1.9 – 30.	1.80	16.8	4.2 – 30.
7.94 – 10.0	0.76	21.2	2.4 – 38.	2.27	21.2	5.3 – 38.
10.00 – 12.6	1.00	30.0	3.4 – 48.	2.85	26.7	6.7 – 48.





